CMOS Charged Particle Spectrometers

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ABSTRACT

Integrated circuits, manufactured in CMOS technology, have been developed as diffusion-based charged particle spectrometers for space applications. Current designs are single-chip spectrometers capable of uniquely identifying and counting electrons and heavy ions. A four-chip spectrometer designed to count protons and heavy ions was flown on the Clementine spacecraft. The spectrometer proton data is compared to GOES-6 proton data for the 21 February 1994 solar proton event.

CMOS PARTICLE SPECTROMETERS

Current CMOS chip spectrometer designs are Active Pixel Sensor (APS) chips that are also being developed by NASA as, light weight, low power, optical imagers [1]. APS spectrometers are being utilized on the Space Technology Research Vehicle-2 (STRV-2) to count trapped protons and electrons. STRV-2 and Clementine spectrometers are fabricated in HP 1.2 μm technology through MOSIS.

Figure 1 shows the HP 1.2 μm technology cross section and the labeling convention used in modeling calibration data, where E2 is the particle energy above the chip, $\Delta E3$ = 132- E3 is the energy lost in the over layer, and $\Delta E4$ = E3 - E4 is the energy deposited in the charge collection layer.

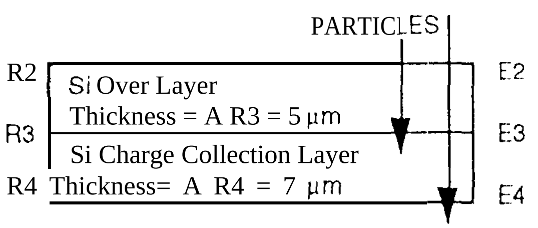

Figure 1. HP 1.2 μm technology labeling convention and layer thicknesses used in modeling calibrations.

Proton energy as a function of range is computed using the fit equation shown in Figure 2. This equation is derived from a fit to the Transport Reactions In Matter (TRIM) [2] computer code. The error bars indicate longitudinal range straggling.

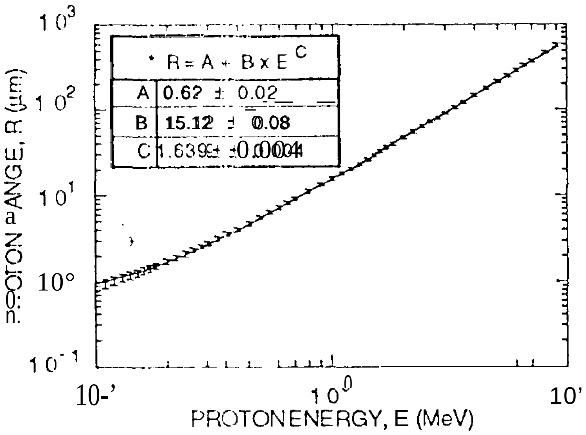

Figure 2, fit to TRIM generated proton range as a function of energy in silicon. The error bars indicate longitudinal straggling.

The Clementine proton spectrometer design, SRAM cell, is an integral spectrometer [3]. All particles depositing more than the threshold energy are counted. Representative chips from the flight fabrication run were calibrated using the Caltech Tandem Van de Graaff proton accelerator. Calibration data was taken at normal incidence with 0.75, 1.0, and 2.0 MeV protons. The mean value threshold energies, where half the protons are counted, are plotted in Figure 3. The proton calibration data points are the mean values of the delta offset voltage, ΔV_p, where one-half the protons hitting a cell sensitive volume cause the cell to flip. The delta offset voltage is the operating offset voltage minus the spontaneous ftip voltage. The spontaneous flip voltage is the offset voltage value where one-half the SRAM cells have Spontaneously flipped.

The proton data calibrated the 1.2 μm technology SRAM at an upset capacitance, C_u/K = 2.667 (MeV/V), where K = 44.2 (fC/MeV) for proton produced ionization per unit energy loss in silicon. The measured energy, $\Delta E4$ shown in Figure 3, is given by, $\Delta E4 = (C_u/K) \times (\Delta V_p)$. The 1 MeV energy window, shown in Figure 3, is the measure of the SRAM response to protons in the space environment. The response curves are computed by solving the TRIM fit equation shown in Figure 2 for energy as a function of range. The maximum corde lengths are $\Delta R3$ = 6.78 μm and $\Delta R4$ = 11.46 μm.

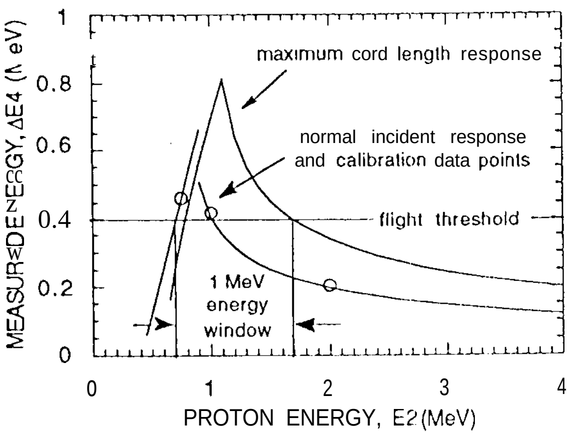

Figure 3. Clementine proton calibration curves showing the flight energy threshold and the 1 MeV wide energy window above the flight threshold.

CLEMENTINE DATA

On Clementine the proton energy spectrum was measured by counting protons in the 1 MeV wide energy window with four chips each behind a different shielding thickness. The shields consisted of 10 mil kovar chip lids. The O-lid chip had a hole drilled through its lid over the chip and the hole was covered with a 1 mil aluminium equivalent aluminized kapton dust cover. The chip-lid shields reduced the external environment proton energy and flux. The flux reduction is given by the environment fractions, fe. The environment fractions were computed with the Novice code from a 2π-sr omnidirectional fluence of 1.96E9 (protons/cm^2-MeV) at all energies (0.1 to 100 MeV) outside the shields. The proton fluence is reduced by the amount f_e inside the shields. The resulting environment fractions as a function of proton energy inside the shields is shown in Figure 4. The 1 MeV wide energy window is also shown.

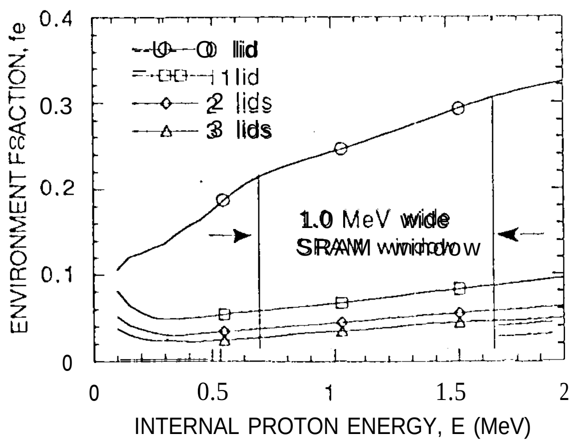

Figure 4. environmental fraction as a function of proton energy inside lid shields. The 1 MeV wide proton sensitive window is shown.

Table 1 lists the external environment energy windows, Emin to Emax, measured in the 1 MeV wide energy window shown in Figures 3 and 4, as a function of shield thickness. The mean value of the environment fractions inside the energy window are also listed in table 1.

Table 1. external environment energy windows and internal environment fractions, f_e, as a function of shielding.

kovar shields (ch# - roils)	Emin (MeV)	Emax (MeV)	f_e mean value (0.7-1.7 MeV)
P1 - 0	2.16	3.16	0.261±0.031
P2 -10	11.81	12.81	0.072?0.009
P3 -20	16.96	17.96	0.047±0.007
P4 -30	21.04	22.04	0.037±0.006

The Clementine spectrometer is sensitized to protons for 100 seconds, every other 100 second period, for one hour, giving an on time fraction, f_{on}, of 0.5. During the other 100 second period the threshold is lifted above the computed peak value, shown in Figure 2 for protons, to measure proton induced nuclear reactions. The energy window width, ΔE measured in Figure 2, is 1 MeV. The instrument is designed with a 2π-sr field of view, Ω. The pixel sensitive area has an as drawn cross section, σ, of 42. 12 μm^2. Each pixel can only count one proton in each 100 second proton sensitive period and there are 18 sensitive periods each hour. There are 4096 pixels, N_T, on each chip and N is the measured number of counts per hour in each chip. The spectrometer measured hourly fluence, F, in units of (protons/cm^2-sr-MeV-hr) outside the shields is given by,

$$F = \frac{18}{\sigma\, \Omega\, \Delta E\, f_c\, f_{on}} \ln\left(\frac{N_T}{N_T - N/18}\right) \qquad (1)$$

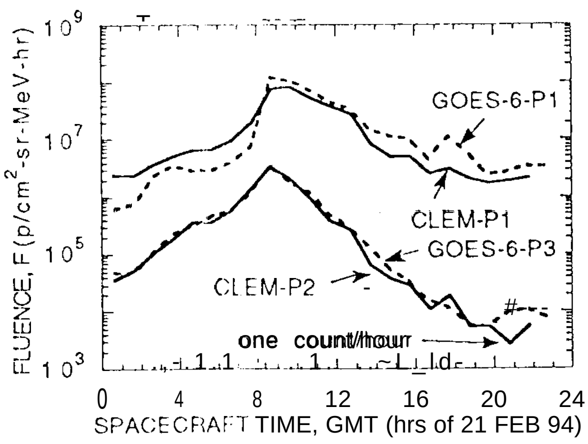

Figure 5, comparison of Clementine data to GOES-6 data during the 21 Feb. 94 solar proton event. The proton spectrometer sensitivity of one count per hour is shown.

The Clementine spectrometer, F from Equation 1, and GOES-6 hourly fluencies arc plotted in Figure 5. The GOES-6 external-environment protcm-energy windows, Emin and Emax, are, P1 = 0.6 to 4.2 MeV, P2 = 4.'2 to 8.7 McV, P3 = 8.7 to 14 McV, and P4 = 15 to 44 MeV.

The Clementine and GOES-6 energy spectra for the total measured fluence on 21 Feb. 94 are shown in Figure 6. The data point energies are taken at the center of the energy windows, (Emin + Emax)/2, listed in Table 1 for the Clementine instrument and above for the GOES-6 instrument.

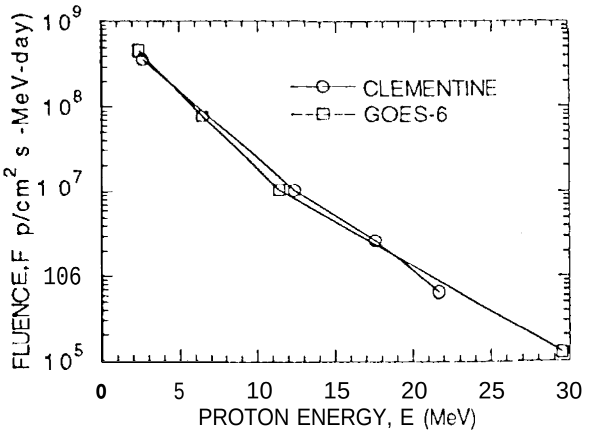

Figure 6, Clementine spacecraft and GOES-6 external environment proton energy spectra on 21 Feb. 94.

APS SPECTROMETER BENEFITS

Particle identification regions are shown in Figure 7. The measured energy in these regions is unique for each particle type. The APS design (Source Follower) is a differential spectrometer where the pulse height associated wilh each measured energy is histogrammed into a differential energy spectrum. This allows the APS to operate with unity on-time fraction, f_{on}.

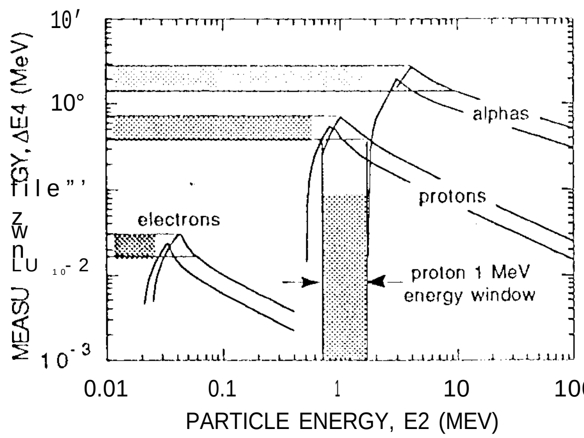

Figure 7. HP 1.2 μm technology measured energy regions that arc unique to each particle type and again the proton 1 MeV wide energy window.

The APS design also extends CMOS spectrometers into the electron region shown in Figure 7. 'he APS room temperature noise floor is measured with 5.9 keV X-rays and this is compared to the SRAM spontaneous flip curve derivative in Figure 8. The APS X-ray spectrum was taken after a 1 krad silicon total CO-60 dose. The APS noise is about one quarter fixed pattern, one half kTC, and onc half all other sources including radiation induced dark current. These effects and [here fabrication, design, and operational solutions arc being studied at [his time. The SRAM noise is fixed pattern dominated, radiation insensitive, and has no dark current component.

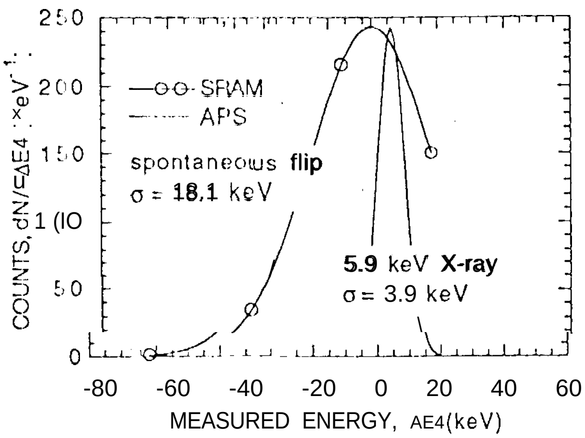

Figure 8. APS unity gain calibration at room temperature showing 55-Fe X-ray peak fit and the SRAM spontaneous flip curve derivative.

CON('LLJS1ONS

The CMOS charged particle spectrometer 1 McV wide energy window and shield filter approach to measuring charged particle energy spectrum in space has been proven as a low mass and low power method. The differential spectrometer APS design approach allows unity on time fraction operation. The APS noise floor extends the CMOS charged p.article spectrometer method into the electron region. The STRV-2 flight will verify the APS CMOS charged particle spectrometer as a low cost method of collecting trapped charged particle data for replacing AE8 and AP8 models, the international radiation design standards used in earth orbiting spacecraft design.

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